A renormalization group analysis of medium-modified fragmentation in SIDIS

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In collaboration with Ivan Vitev, *2301.11940 and works in preparation*

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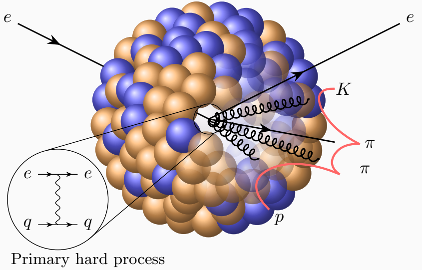
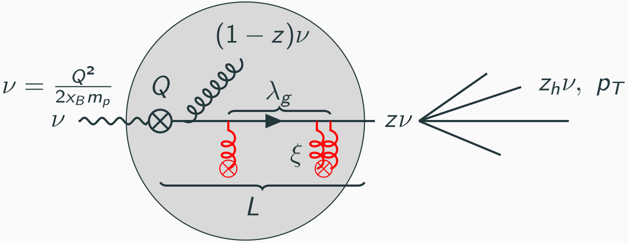
Fragmentation in cold nuclear matter via semi-inclusive DIS

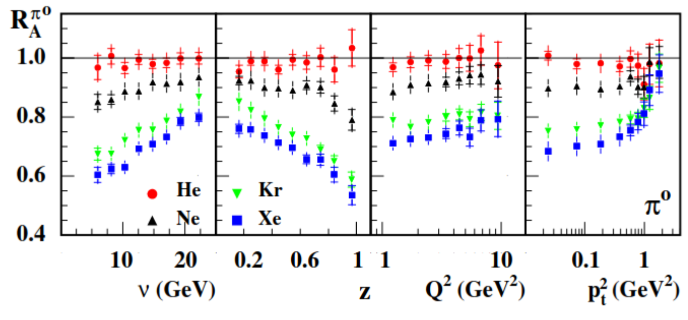




SIDIS with nuclear targets probes parton dynamics in cold nuclear matter. An interplay of jet energy scale ($Q, E = z\nu$) and multiple medium scales:

- In-medium path length L.
- Mean free path of parton-medium rescattering λ_g.
- Inverse scattering range of rescattering $\xi \gtrsim \Lambda_{\mathrm{QCD}}$.

Sizeable nuclear modifications in SIDIS observed at EMC, HERMES, CLAS



$$R_A^h = \frac{N_{eA\to\pi^0}(z_h, p_T^2; \nu, Q^2)}{N_{ed\to\pi^0}(z_h, p_T^2; \nu, Q^2)}$$

$$N_{eX\to h} = \frac{d\sigma_{eX\to h}}{d\nu dQ^2 dz_h dp_T^2} \Big/ \frac{d\sigma_{eX}}{d\nu dQ^2}$$

EMC ZPC52(1991)1–11

◁ HERMES NPB780(2007)1-27

CLAS PRC105(2022)015201

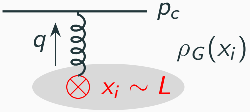
- Are these modifications (at least partly) perturbatively calculable?
- What are the NP inputs to understand data and to characterize the cold nuclear matter?

An EFT approach to in-medium parton dynamics: SCET$_G$

Soft-Collinear-Effective-Theory with Glauber gluon [A. Idilbi, A. Majumder PRD80(2009)054022, G. Ovanesyan, I. Vitev, JHEP06(2011)080] .

- Collinear mode $p_c \sim (1, \lambda^2, \lambda)\nu$ and soft mode $p_s \sim (\lambda^2, \lambda^2, \lambda^2)\nu$ from SCET.
- Glauber gluon $q \sim (\lambda^2, \lambda^2, \lambda)\nu$. Background field from medium sources $(x_1, x_2, \cdots x_i, \cdots)$

$$A_G^{\mu,a}(q) = \sum_i \frac{-g_s e^{-iq^- x_i^+}}{\mathrm{q}_\perp^2 + \xi^2} \langle X | J^{\mu,a} | i \rangle$$



- Medium-size sensitive modes have $p^- \sim \frac{1}{L} \Longrightarrow \lambda = \frac{1}{\sqrt{\nu L}}$.
  - $p_c^2 \sim q^2 \sim \nu \cdot \frac{1}{L}$ a semi-hard scale for thin medium!
  - $p_s^2 \sim 1/L^2$, non-perturbative.

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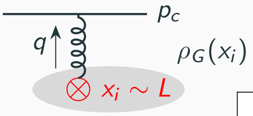

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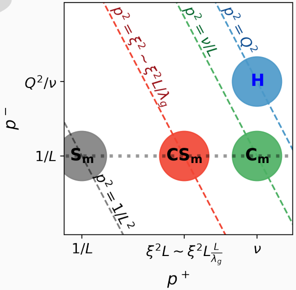
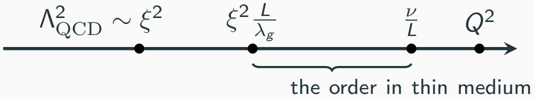
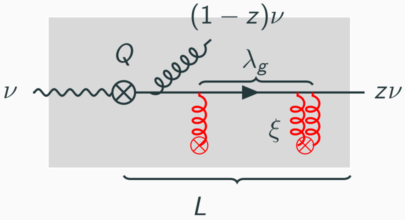


Scale separation in a thin/dilute medium

- Consider eA DIS at moderately large x_B ($x_B \gtrsim 0.1$) such that $\frac{\nu}{L} \sim \frac{Q^2}{10 x_B A^{1/3}} < Q^2$.
- "The semi-hard scale $\frac{\nu}{L}$" $\gg$ "the average q_T^2 transfer $\xi^2 \frac{L}{\lambda_g}$".
- This work further assumes $L/\lambda_g = \mathcal{O}(1)$.





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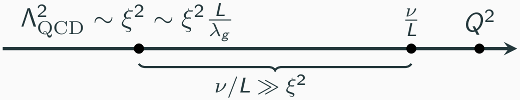
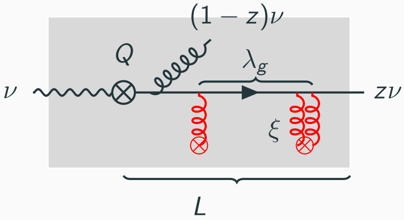
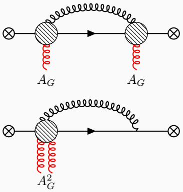




The single-hadron SIDIS cross section with $\nu/L \gg \xi^2$

$$\frac{d\sigma_{ep\to h}}{dx_B dQ^2 dz_h} = \frac{2\pi\alpha_e^2}{Q^4}\sum_{i,j}\underbrace{e_q^2 f_{i/A}(x_B)\otimes C_{ij}^h(x,z)}_{F_{ij}(z)}\otimes d_{h/j}(z_h)$$

$$\frac{d\sigma_{eA\to h}}{dx_B dQ^2 dz_h} = \sum_{i,j}\frac{2\pi\alpha_e^2}{Q^4}\left[F_{ij}(z) + \Delta F_{ij}^{\mathrm{med}}(z)\right]\otimes d_{h/j}(z_h)$$



- $\Delta F_{ij}^{\mathrm{med}}(z) = F_{ik}^{(0)} \otimes P_{kj}^{\mathrm{med}(1)}$ are corrections from medium-induced parton splittings.
- $P_{kj}^{\mathrm{med}(1)}$ are complicated, and past studies often rely on numerical approach/MC.
- We use analytic approach to gain understanding & insights for in-medium factorization.

The key observation: $P_{ij}^{\mathrm{med}(1)}$ constains endpoint divergences

- Endpoint divergences appears because all masses (ξ^2, etc) are dropped according to collinear power counting $\xi^2 \ll \nu/L$. For example, the flavor non-singlet spectrum

$$\Delta F_{\mathrm{NS}}^{\mathrm{med}}(z) = \int_z^1 \frac{dx}{x} F_{\mathrm{NS}}(\frac{z}{x}) P_{qq}^{\mathrm{med}(1)}(x) \quad + \quad \text{virtual term.}$$

$$P_{qq}^{\mathrm{med}(1)}(x) = A(\alpha_s, \cdots) \cdot \frac{P_{qq}^{vac(0)}(x)}{[x(1-x)]^{1+2\epsilon}} \cdot \left[\frac{\mu^2 L}{\chi z \nu}\right]^{2\epsilon} \cdot C_n \Delta_n(x)$$

- They can be regulated using dimension regularization ($d = 4 - 2\epsilon$),

$$\Delta F_{\mathrm{NS}}(z) = A(\alpha_s, \cdots) \left(\frac{1}{2\epsilon} + \ln \frac{\mu^2 L}{\chi z \nu}\right) 2C_F [\underbrace{2C_A \left(-\frac{d}{dz} + \frac{1}{z}\right)}_{\text{from } x\to 1} + \underbrace{\frac{C_F}{z}}_{x\to 0}] F_{\mathrm{NS}}(z) + \text{F.O.}$$

- Absorb divergence with an in-medium renormalization $F_{ij} \longrightarrow \left(M_{ik}^{(0)} + \frac{1}{\epsilon} M_{ik}^{(1)}\right) \otimes F_{kj}$. It suggests another relevant sector (collinear-soft) as μ^2 approaches ξ^2 (or $\xi^2 L/\lambda_g$).

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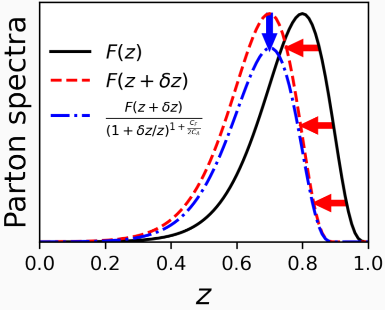
RG equations for the collinear sector

- Define $\tau(\mu^2) = \frac{\rho_G L^2}{\nu}\frac{\pi B}{2\beta_0}\left[\alpha_s(\mu^2) - \alpha_s\left(\chi\frac{z\nu}{L}\right)\right]$ evolving from $\mu^2 = \chi\frac{z\nu}{L}$ down to ξ^2. Depend on Q^2 only through coefficients B and $\chi > 3.0$.

$$\frac{\partial F_{\mathrm{NS}}(\tau,z)}{\partial\tau} = \left(4C_F C_A\frac{\partial}{\partial z} - \frac{4C_F C_A + 2C_F^2}{z}\right)F_{\mathrm{NS}}$$



A "traveling wave" solution for F_{NS}

$$F_{\mathrm{NS}}(\tau,z) = \frac{F_{\mathrm{NS}}\left(0, z + 4C_F C_A\tau\right)}{(1+4C_F C_A\tau/z)^{1+C_F/(2C_A)}}$$

The primary effect: shift spectra by $\delta z = -4C_F C_A\tau$.

The parton energy loss picture $\Delta E = \nu\delta z \propto \rho_G L^2$.

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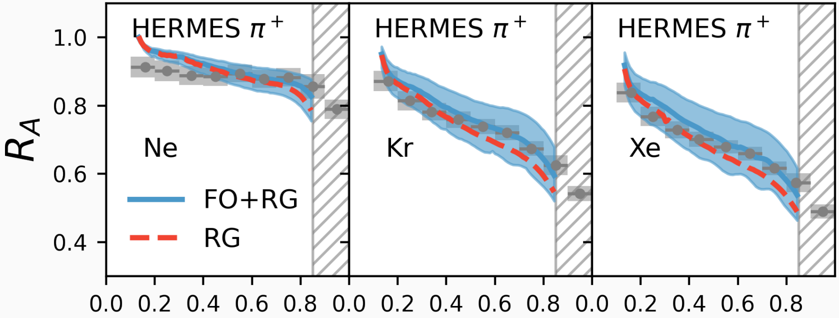
- Flavor singlets F_g and $F_f = F_q + F_{\bar{q}}$, for $f = u, d, s$.

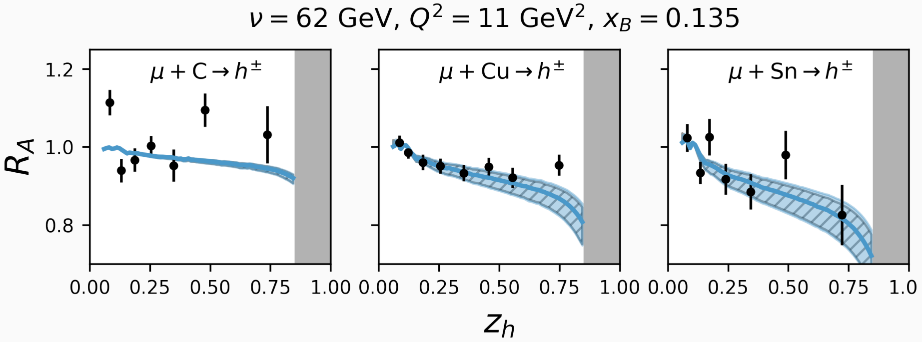
$$\begin{aligned}
\frac{\partial F_f}{\partial \tau} &= \left(4 C_F C_A \frac{\partial}{\partial z} - \frac{4 C_F C_A + 2 C_F^2}{z}\right) F_f + 2 C_F T_F \frac{F_g}{z}, \\
\frac{\partial F_g}{\partial \tau} &= \left(4 C_A^2 \frac{\partial}{\partial z} - \frac{2 N_f C_F}{z}\right) F_g + 2 C_F^2 \sum_f \frac{F_f}{z}.
\end{aligned}$$

Comparison with HERMES data [NPB780(2007)1-27]



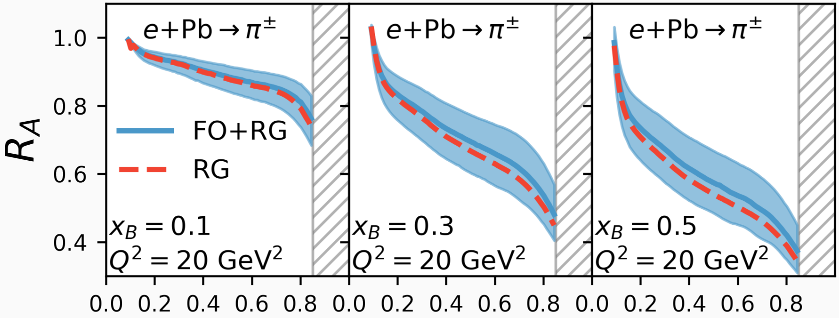
- Baseline: NLO DIS and SIDIS cross sections. NNFF1.0LO vacuum FF [EPJC77(2017)516] and nNNPDF3.0 nuclear PDF [EPJC82(2022)507] .
- Calculated with averaged HERMES $\langle Q^2 \rangle \approx 2.25$ GeV, $\langle \nu \rangle = 12$ GeV.
- Central values tuned to $\xi = 0.35$ GeV, $\rho_G = 0.4\ \mathrm{fm}^{-3}$. Band: $\left(\frac{2}{3}, \frac{3}{2}\right) \rho_G$
- Good agreement except for the region $z_h \to 1$ (not dominated by collinear modes).

Comparison with SIDIS at EMC [ZPC52(1991)1–11]



- Such effects were observed at EMC at higher $\langle Q^2 \rangle = 11$ GeV^2 and $\langle \nu \rangle = 62$ GeV.
- **Same value of parameters** (ξ, ρ_G) **as used for HERMES**. Bands: $(\frac{2}{3}, \frac{3}{2})\xi^2$, $(\frac{2}{3}, \frac{3}{2})\rho_G$.

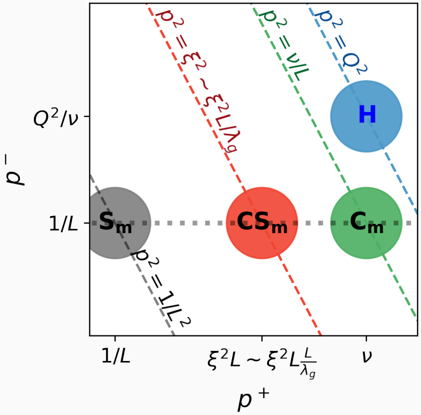
Projection for EIC: ePb versus ep



- Same parameters, but expects smaller effects at small x_B as parton too energetic in the nuclear rest frame. From left to right: $\nu = 107$ GeV, 36 GeV, 21 GeV
- EIC will enable a fully differential scan in a large range of ν, Q^2.

Towards a factorization formula for fragmentation in eA?

- Medium-size sensitive modes have $p^- \sim 1/L$.
- We have identified the semi-hard scale in the problem $p^2 \sim \nu/L$ for a thin medium.
- *Ongoing & preliminary*: including medium-induced collinear-soft CS_m with $p^2 \gtrsim \xi^2$. Relevant for the correct description as $z_h \to 1$.
- A formal definition of nuclear NP inputs.



Summary and Future

- In-medium fragmentation is a multi-scale problem and contains perturbative & NP physics.
- For thin medium, we identify the semi-hard scale ν/L for medium-induced collinear modes $\Longrightarrow$ a region for perturbative treatment.
- The first in-medium NLO calculation using the RG analysis.

  A partial-differential RG equation follows from endpoint divergences in the collinear sector.

  Simple RG solutions were obtained with a clear physical interpretation.
- Phenomenological parameters ξ^2, ρ_G tuned to HERMES SIDIS data

  $\Longrightarrow$ good descriptive power at both HERMES and EMC energy.
- Towards a factorization formulation and formal definition of NP nuclear parameters.

Questions?

Connection to the modified DGLAP equation

The medium-modified DGLAP are widely used phenomenology approach in both *eA* and *AA*

$$\frac{\partial}{\partial \ln \mu^2} D_{h/i} = [P_{ij}^{\rm vac} + \Delta P_{ij}^{\rm med}]_+ \otimes D_{h/j}$$

- In numerical solver, all divergences in $\Delta P_{ij}^{\rm med}$ are screened by a mass

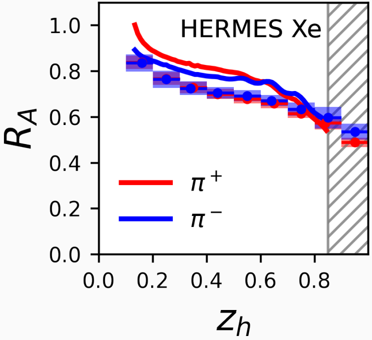
$$\mathrm{k}_\perp^2 > \xi^2 \quad \Rightarrow \quad x, (1-x) > \frac{\xi^2}{\mu^2}$$

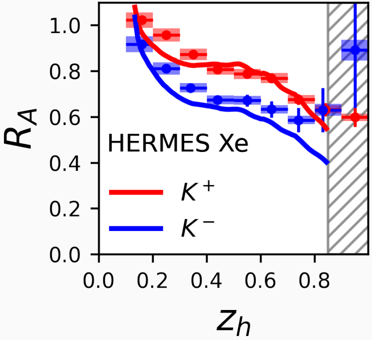
- The mDGLAP (a simplified version) can be Taylor expanded around, e.g., $x = 1$,

$$\begin{aligned}\frac{\partial F_{\rm NS}}{\partial \ln \mu^2} &= 4 C_F C_A A_0 \int_0^{1-\frac{\mu_D^2}{\mu^2}} \frac{4}{\pi} \frac{\Phi(\frac{\mu^2 L}{2E})}{\frac{\mu^2 L}{2E}} \frac{\left(\frac{x}{z}\right) F_{\rm NS}(\frac{z}{x}) - \frac{F_{\rm NS}(z)}{z}}{(1-x)^2} dx \\ &= \frac{4}{\pi} \frac{\Phi(\frac{\mu^2 L}{2E})}{\frac{\mu^2 L}{2E}} \times 4 C_F C_A A_0 \ln \frac{\mu^2}{\mu_D^2} \left[\frac{\partial F_{\rm NS}}{\partial z} - \frac{F_{\rm NS}}{z}\right] + \text{non-log-enhanced terms}\end{aligned}$$

- Same leading-log physics as the RG approach (if one chooses $\mu^2 = \mathrm{k}_\perp^2/[x(1-x)]$).

Pion vs Kaon





- Change to DSS parametization for $\pi^{\pm}$ and $K^{\pm}$ fragmentation function. D. Florian et al. PRD75(2007)114010 and PRD91(2015)014035

Ongoing: higher-order in opacity?

- Complexity of in-medium splitting function blows up with opacity $N = 1, 2 \cdots$.
- Assume the leading contribution still comes from the endpoint region, especially near $x = 1$.
- The opacity $N = 2$ contributions leads to two types of corrections:

$$
\begin{aligned}
& \alpha_s C_R \frac{\mu_G^2}{E/L} \cdot [\underbrace{a_1 \partial_z + \cdots}_{N=1} + \underbrace{a_2 \frac{\mu_G^2}{\xi^2} \partial_z + b_2 \frac{\mu_G^2}{E/L} \partial_z^2 + \cdots}_{N=2}], \qquad \mu_G^2 = \alpha_s \rho_G L \\
= \quad & \alpha_s C_R \frac{\mu_G^2}{E/L} \cdot \left[\left(a_1 + a_2 \frac{\mu_G^2}{\xi^2} \right) \partial_z + b_2 \frac{\mu_G^2}{E/L} \partial_z^2 + \cdots \right]
\end{aligned}
$$

It is interesting to investigate whether the opacity expansion leads to a gradient expansion of the evolution equation.